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DAVID W. TAYLOR NAVAL SHIP
RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

CAVITATION-FREE BUCKETS OF YS-920 AND NACA 66 (MOD) FOIL SECTIONS

By

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DEPARTMENT REPORT

July 1982

DTNSRDC/SPD-1049-01

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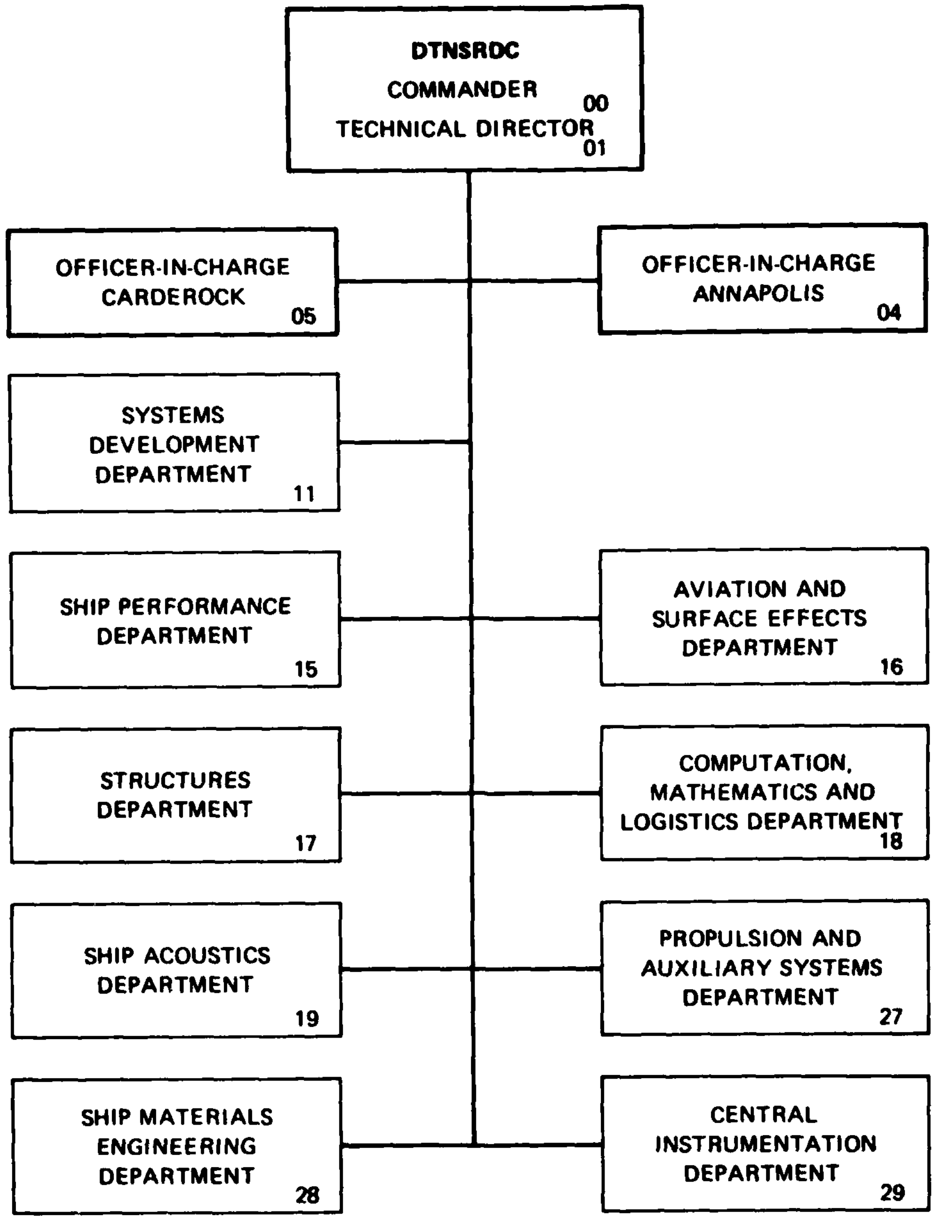

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DTNSRDC/SPD-1049-01	2. GOVT ACCESSION NO. AD-A118 104	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) CAVITATION-FREE BUCKETS OF YS-920 AND NACA 66 (MOD) FOIL SECTIONS		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Y. T. Shen		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS David W. Taylor Naval Ship R&D Center Bethesda, Maryland 20084		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Element No. 61153N Task Area: SR 0230101
11. CONTROLLING OFFICE NAME AND ADDRESS David W. Taylor Naval Ship R&D Center General Hydrodynamic Research Program Bethesda, Maryland 20084		12. REPORT DATE
		13. NUMBER OF PAGES 13
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Hydrofoil Section
Cavitation Inception
Water Tunnel Experiments
Cavitation-Free Bucket
Section Design
Boundary Layer Separation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Based on a wing section design theory and boundary layer calculations, a new series of hydrofoil sections with improved cavitation inception characteristics were theoretically developed and presented in previous papers. To verify these theoretical results experimentally, two hydrofoil models, one a newly developed profile designated YS-920 and the other an NACA-66 (MOD) wing section, were tested in a high-speed water tunnel ~~at~~ California Institute of Technology. The measurements included force and moment data, flow visualization, cavitation characteristics, and surface -

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Block #20 ABSTRACT

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Based on a wing section design theory and boundary layer calculations, a new series of hydrofoil sections with improved cavitation inception characteristics were theoretically developed and presented in previous papers. To verify these theoretical results experimentally, two hydrofoil models, one a newly developed profile designated YS-920 and the other an NACA 66 (MOD) wing section, were tested in a high speed water tunnel at California Institute of Technology. The measurements included force and moment data, flow visualization, cavitation characteristics, and surface roughness effect on cavitation. In this report, the measured cavitation-free buckets of YS-920 and NACA 66 (MOD) foil sections are presented and compared with theoretical predictions. The ability to achieve a significant delay in cavitation inception with a newly designed profile is clearly demonstrated experimentally.

ADMINISTRATIVE INFORMATION

The work carried out in this experimental investigation was supported by Naval Sea Systems Command, Code 035 under the General Hydrodynamic Research Program, Element 61153N, Task Area SR 0230101.

INTRODUCTION

When operated at a practical depth below the free surface, a lifting surface will develop vortex cavitation and surface cavitation on the foil above a certain critical speed. Foil cavitation leads to undesirable changes in hydrodynamic and

acoustic characteristics and possible damage to the foil structure. Consequently, the design philosophy of current hydrofoil and propeller blade sections is governed by the requirements of (1) providing specified lift, (2) avoiding or minimizing cavitation, and (3) supplying adequate structural strength for all operating conditions.

In a seaway, the lifting surfaces of a hydrofoil craft experience significant changes in the angle of attack due to both wave orbital velocities and craft motion. Similarly, for a propeller operated behind an inclined shaft and in a ship wake, the propeller blades experience periodic variation in effective angle of attack.

The physical process associated with inception of cavitation is extremely complex. However, it has been generally agreed that cavitation inception occurs on a full-scale lifting surface when the local pressure falls to or below the vapor pressure of the flowing fluid. Cavitation inception can be predicted from the pressure distribution, since the cavitation-inception index $\sigma_i = \sigma$ is equal to the negative minimum pressure coefficient $-C_{pmin}$. The hydrodynamic characteristics of a hydrofoil section to delay the occurrence of surface cavitation can then be examined in terms of a so-called minimum pressure envelope, often referred to as the cavitation-free bucket. For a specified hydrofoil section the internal region of the minimum pressure envelope defines the region of cavitation-free section lift coefficients (or angles of attack) as a function of section cavitation number.

NACA 16 - series and NACA 66 (MOD) - series wing sections are known to have good characteristics for delaying inception of cavitation. Extensive application of these two series of NACA wing sections to existing hydrofoil craft and marine propellers has been well documented [1,2]. Since, the NACA wing sections were

developed around 1940, possible areas of improvement have been investigated both theoretically and experimentally; see Reference [3]. By means of recently developed wing section design theory, a series of new hydrofoil sections has been theoretically investigated by Shen and Eppler [3,4,5] with noticeable improvement of predicted surface cavitation inception. This encouraging result calls for experimental verification.

The present report provides a comparison of experimentally measured and theoretically predicted cavitation-free buckets of newly designed YS-920 and NACA-66 (MOD) sections.

EXPERIMENTAL EQUIPMENT

WATER TUNNEL

The High-Speed Water Tunnel (HSWT) in the Graduate Aeronautical Laboratories of the California Institute of Technology was used in the present investigation. This water tunnel is equipped with a two-dimensional working section. The model can be viewed through top, bottom and side windows. Further descriptions of this water tunnel are given in Reference [6].

HYDROFOIL MODELS

The design lift coefficient of $C_L = 0.2$ is a typical value used in hydrofoil and propeller blade section design. The profile YS-920 which has a design lift coefficient of 0.22 was thus selected from Reference [5] for this investigation. The profile shape, coordinate offset, and the design philosophy of this profile were given in Reference [5]. A NACA 66 (MOD) wing section with a camber ratio of $f/c = 0.020$ was also selected in this investigation. The camber ratio of the NACA 66 (MOD) section was selected in such a way that both foils YS-920 and NACA 66

(MOD), have about the same lift coefficient of $C_L = 0.22$ at the center of their cavitation buckets. Furthermore, both profiles have the same maximum thickness-to-chord ratio of 0.09.

For testing in the HSWT, both hydrofoil models had six-inch chord (15.2 cm) and six-inch span. The models were made from 17-4 PH stainless steel hardened to the H 1075° F (579° C) condition. To ensure a very accurate surface contour, both models were cut from the blocks by a numerical controlled machine using a total of 850 passes on each foil surface. Deviations from the specified section profiles measured normal to the surface at 3 stations along the span were found to be less than 0.0005 of the chord length. The coordinates and profile shape of YS-920 along with velocity distributions at three foil angles are given in Table 1 and Figure 1, respectively.

DISTRIBUTED SURFACE ROUGHNESS

Profile YS-920 was designed to have no flow separation on the foil surface at a typical full-scale Reynolds number value of 3×10^7. Thus, if the YS-920 profile were used for a prototype, boundary layer calculations indicate that the boundary layer on the foil surface will go through a natural transition from laminar to turbulent near the leading edge. The boundary layer calculations also show that due to the reduction in Reynolds number for the hydrofoil model tested in the water tunnel (HSWT) laminar boundary layer separation will be encountered near the trailing edge. To simulate the high Reynolds number phenomenon, the models were also tested with surface roughness uniformly distributed near the leading edge, over 1.5 percent of the chord length on the upper and lower surfaces. The surface roughness consisted of glass spheres of 0.004 inch (0.010 cm) nominal diameter bonded to the surface of the foil section with Loctite General Purpose Epoxy 53.

EXPERIMENTAL RESULTS

The majority of the experiments were conducted at a tunnel water speed of 50 feet per second (15.2 meters per second), corresponding to a Reynolds number based on the chord length of 2.6×10^6 [7]. Flow visualization observations confirmed the boundary layer calculations, that at the design condition of C_L = 0.22 the hydrofoil model of YS-920 did experience laminar boundary layer separation near the trailing edge. Without the installation of surface roughness, the model experienced a band-type cavitation around the measured laminar boundary layer separation zone. With the installation of surface roughness uniformly distributed around the leading edge, the band-type cavitation associated with laminar boundary layer separation was completely eliminated, and the model experienced a traveling bubble type cavitation as is to be anticipated in the prototype. At a large angle of attack, namely a large lift coefficient, the foil experienced leading edge sheet cavitation.

The measured cavitation-free buckets of YS-920 and NACA 66 (MOD) with and without surface roughness are given in Figures 2 and 3. Without the installation of surface roughness, the foil surface is denoted as smooth. The theoretically computed cavitation-free buckets of these two wing sections are also shown in the same Figures for a direct comparison.

Without the application of surface roughness, when the foil surface is smooth, the measured cavitation-free buckets are seen to be much wider than the theoretically predicted bucket. As predicted from the theoretical computations (See Figure 2), experimental measurements confirmed that the danger of cavitation inception on the pressure side of Profile YS-920 is greatly delayed as compared to that on the NACA 66 (MOD) section.

With the application of leading edge surface roughness, the measured cavita-

tion free buckets show a remarkable agreement with the theoretically predicted buckets. As predicted from the theory, the measured cavitation-free bucket of Profile YS-920 is significantly wider than that of NACA 66 (MOD) section at the design cavitation number $\sigma = 0.45$. The measured bucket widths were found to be around 3.2 and 2.3 degrees in angle-of-attack for Profiles YS-920 and NACA 66 (MOD), respectively. Note, 1 degree in angle-of-attack corresponds to approximately 0.1 in lift coefficient. The measured cavitation inception values are in good agreement with the predicted values given in Figure 11 of Reference [5]. This significant result suggests that at a given design speed, the newly designed Profile YS-920 should be able to tolerate much greater fluctuation (variation in angle-of-attacks than the compared NACA 66 (MOD) section in a non-uniform wake.

CONCLUDING REMARKS

Experimental measurements confirmed the previous theoretical predictions that at a given design speed, the cavitation-free bucket width of the newly developed section profile YS-920 is significantly greater than that of the comparable NACA 66 (MOD) wing section.

The measured bucket widths of Profiles YS-920 and NACA 66 (MOD) were found to be around 3.2 and 2.3 degrees in angle-of-attack, respectively. Consequently, Profile YS-920 should be able to tolerate much greater variation in angle-of-attack than the comparable NACA 66 (MOD) section in a non-uniform wake or sea state.

The thickness-to-chord ratio of practical interest is 0.09 on existing naval hydrofoils. However, the thickness ratio of practical interest on marine propellers is generally less than 0.09 at the outer radii. Due to the reduction in

leading edge thickness, the cavitation-free bucket widths on thin sections would be smaller than the values quoted previously. This fact makes it difficult to operate a thin blade section in a non-uniform flow without cavitation. However, it is believed that a new type of blade section can be designed to delay cavitation inception.

The present experimental investigations and previous theoretical predictions strongly indicate that refining a profile for each application to hydrofoils and propeller blades sections is possible and advantageous in the future.

Further discussion of the measured force and moment data, boundary layer characteristics and cavitation characteristics of Profile YS-920 will be given in a separate report.

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Table 1 Profile 920 coordinates

N	X	Y	N	X	Y	N	X	Y
0	100.000	0.000	41	25.046	5.175	81	23.375	-3.631
1	99.967	.012	42	22.894	4.979	82	25.535	-3.590
2	99.633	.057	43	20.809	4.7	83	27.782	-3.523
3	99.196	.169	44	18.797	4.548	84	30.109	-3.435
4	98.667	.290	45	16.863	4.314	85	32.569	-3.330
5	97.890	.476	46	15.012	4.069	86	34.973	-3.211
6	97.053	.692	47	13.256	3.814	87	37.494	-3.081
7	96.161	.932	48	11.580	3.550	88	40.063	-2.943
8	95.631	1.104	49	10.008	3.280	89	42.673	-2.798
9	93.030	1.452	50	8.537	3.003	90	45.315	-2.648
10	92.527	1.739	51	7.171	2.722	91	47.986	-2.496
11	91.167	2.048	52	5.914	2.437	92	50.661	-2.342
12	89.507	2.377	53	4.769	2.152	93	53.348	-2.188
13	87.976	2.725	54	3.740	1.866	94	56.034	-2.035
14	86.205	3.087	55	2.829	1.583	95	58.709	-1.885
15	84.522	3.459	56	2.039	1.304	96	61.364	-1.738
16	82.699	3.831	57	1.374	1.031	97	63.993	-1.595
17	80.826	4.197	58	.836	.768	98	66.585	-1.457
18	78.915	4.532	59	.429	.514	99	69.133	-1.326
19	76.943	4.812	60	.152	.274	100	71.620	-1.200
20	74.898	5.054	61	.009	.064	101	74.063	-1.081
21	72.765	5.271	62	.046	-.129	102	76.429	-.970
22	70.575	5.462	63	.246	-.344	103	78.719	-.866
23	68.327	5.631	64	.570	-.576	104	80.925	-.769
24	66.025	5.778	65	1.033	-.812	105	83.039	-.680
25	63.677	5.903	66	1.620	-1.054	106	85.056	-.599
26	61.288	6.006	67	2.335	-1.298	107	86.960	-.525
27	58.866	6.089	68	3.172	-1.543	108	88.768	-.457
28	56.416	6.150	69	4.126	-1.785	109	90.450	-.396
29	53.946	6.191	70	5.195	-2.023	110	92.009	-.339
30	51.461	6.211	71	6.375	-2.253	111	93.430	-.287
31	48.968	6.211	72	7.662	-2.475	112	94.733	-.236
32	46.474	6.191	73	9.053	-2.686	113	95.891	-.182
33	43.985	6.152	74	10.544	-2.883	114	96.917	-.124
34	41.508	6.092	75	12.129	-3.065	115	97.811	-.069
35	39.058	6.014	76	13.805	-3.228	116	98.568	-.026
36	36.617	5.918	77	15.567	-3.371	117	99.170	.001
37	34.215	5.803	78	17.408	-3.490	118	99.629	.009
38	31.851	5.670	79	19.325	-3.580	119	99.906	.005
39	29.531	5.521	80	21.310	-3.632	120	100.000	-.000
40	27.264	5.356						

$\beta = 2.65$

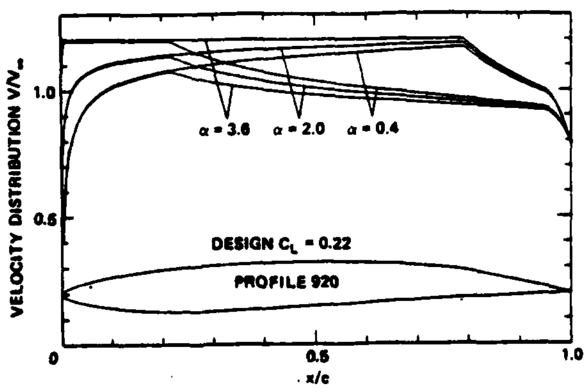

Fig. 1 Velocity distributions of Profile 920

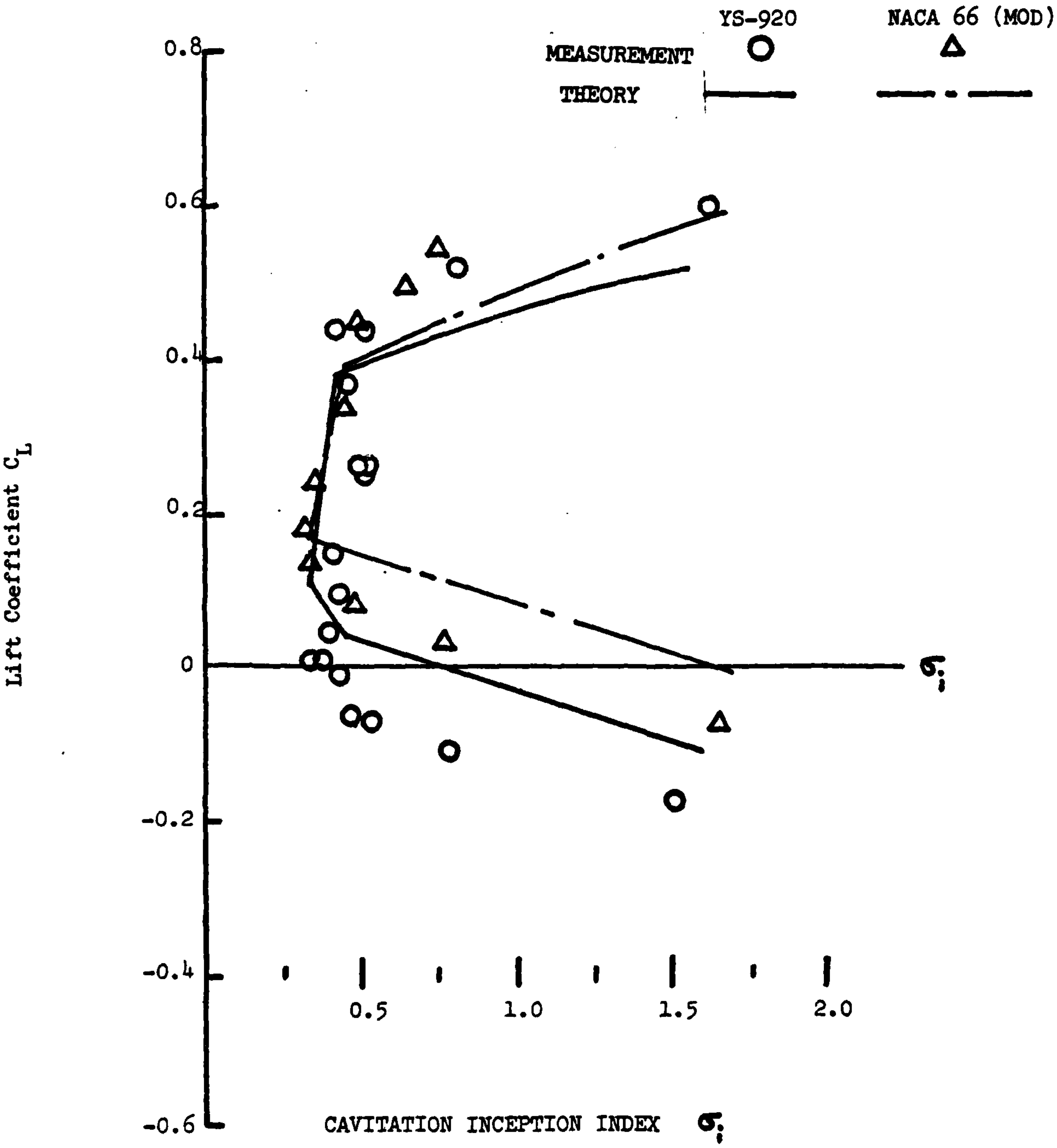

Figure 2 - Cavitation-Free Buckets of YS-920 and NACA 66 (MOD) Sections (Surface Smooth)

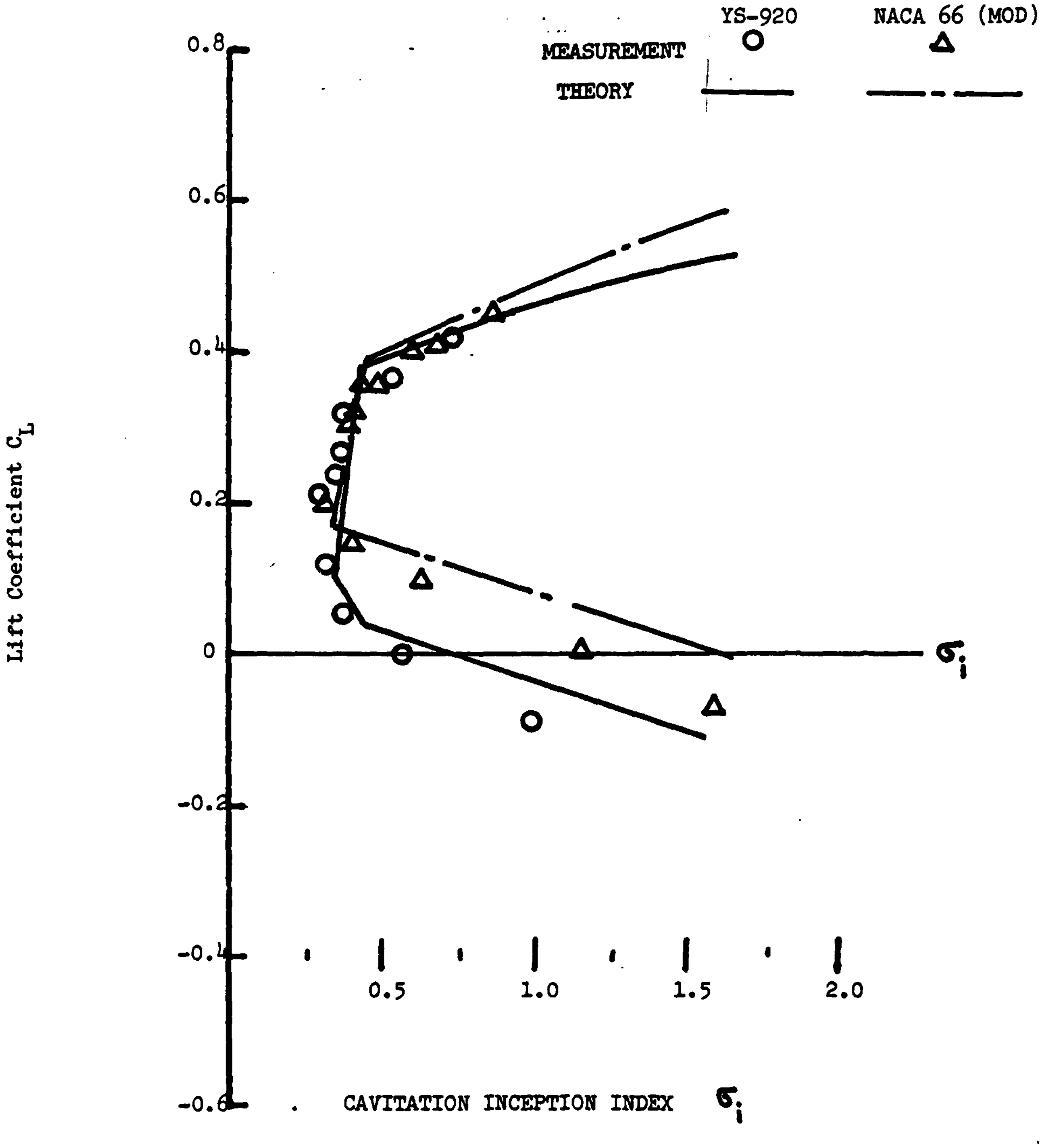

Figure 3 - Cavitation-Free Buckets of YS-920 and NACA 66 (MOD) Sections (Surface Roughened)

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